AUV and ROV Developments at Porto University

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ABSTRACT

In this paper we describe the latest developments in the underwater vehicles built and operated by the Systems and Underwater Technology Lab (LSTS) at the University of Porto. We point out the technological expertise achieved during the last few years through the design, implementation and operation of underwater robotic systems and we address the main challenges for the near future in the shape of new paradigms for systems integration and operation.

1. INTRODUCTION

Traditional techniques for underwater observation are generally expensive and do not offer a comprehensive coverage, especially as the requirements become extremely demanding. On the other hand, recent progresses in underwater technologies have allowed for robotic systems to become highly versatile and, as a consequence, they have been increasingly adopted as efficient and effective tools for underwater observation and intervention.

The LSTS, at the University of Porto, pursues the design and implementation of innovative approaches to underwater observation and intervention by the synergistic interaction between advanced topics in control with the latest developments in underwater technology. The laboratory has been involved in the design and implementation of underwater robotic systems for the last 8 years.

This paper is organized as follows. In section 2 we describe the key features of the underwater vehicles currently operated by LSTS or under construction. In section 3 we describe the key technologies developed at. Finally, in section 4, we present a description of two on-going projects, with the main challenges associated with them and the strategic plan for the next technological developments at LSTS.

2. UNDERWATER VEHICLES

2.1. AUVs

Autonomous Underwater Vehicles (AUVs) constitute powerful and effective tools for underwater data gathering. These vehicles operate with no physical link with the surface, carrying a set of relevant sensors to characterize the underwater environment. The LSTS has been operating and customizing the *Isurus* AUV, for the past 5 years [Cruz99]. *Isurus* (Fig.1) is a REMUS (Remote Environment Measuring UnitS) class AUV, built by the Woods Hole Oceanographic Institution, MA, USA, in 1997. These vehicles are low cost, lightweight, and specially designed for coastal waters monitoring [vonAlt94]. The reduced weight and dimensions makes them extremely easy to handle, requiring no special equipment for launching and recovery. *Isurus* has a torpedo shaped hull, about 1.5 meters long, with a diameter of 20 cm and weighting about 35 kg in air. Inside the hull several subsystems have been improved or specifically developed at LSTS, contributing to the enhancement of the vehicle's performance and reliability. The maximum forward speed is 4 knots, being the best energy efficiency achieved at about 2 knots. At this velocity, the energy provided by a set of rechargeable Lithium-Ion batteries may last for over 20 hours (i.e., over 40 nautical miles).

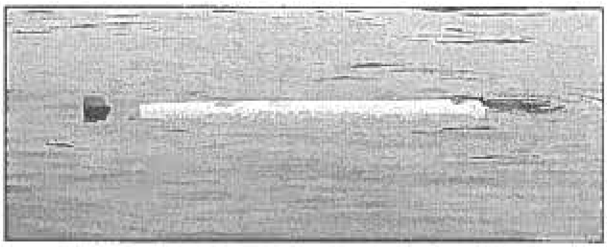

Fig.1 - The *Isurus* AUV at the surface

Although small in size, this vehicle can accommodate a wide range of oceanographic sensors, such as CTD, Altimeter, Sidescan Sonars, ADCP, or Optical BackScatter,. The principal characteristics of the Isurus AUV are summarized in the following table:

Current Sensors	CTD, *OS200* (Ocean Sensors) Light Scattering Sensor, (Wet Labs) Sidescan Sonar (Marine Sonic Technology) Echosounder (Imagenex)
Optional Sensors	Clorophyll Fluorometer Dissolved Oxygen Video Camera
Navigation	Digital Compass, *TCM2* (PNI) Acoustic Beacons, LBL 20-30KHz
Actuation	Main propeller, 24VDC Motor, 80W (Maxon) Horizontal and Vertical Fins
On-board Computer	PC-104 Technology QNX Real Time Operating System

The first operational missions with *Isurus* took place in 1998, in the estuary of the river Minho, in the northern border between Portugal and Spain. During autonomous missions, typically longer than one hour, the vehicle continuously collected CTD and bathymetric data, while navigating on a LBL transponder network.

These missions demonstrated the reliability and the operational effectiveness of this vehicle and, since then, several other missions have been performed on different scenarios. Last summer, on an innovative mission, the vehicle has been used as part of a monitoring plan for a sewage outfall, 3 km off the Portuguese coast. The vehicle successfully performed a 2 hours mission, under very severe sea conditions.

The experience obtained from operational missions allowed for an exhaustive characterization of the capabilities and limitations of the complete system. Cooperation with mechanical engineers from INEGI resulted in the identification of a set of key features to allow for significant improvements, resulting in a new design (Fig. 2) that is being assembled and is expected to be ready during the summer of 2003. These improvements in the mechanical design consist in:

- Utilization of lighter composite materials in the central hull, saving valuable weight to incorporate new sensors and electronics.
- Increased modularity to ease the reconfigurability of the vehicle depending on the missions to be performed.
- Incorporation of a radio link to allow for wireless communication when the vehicle is at the surface, avoiding recovery for data transfer.

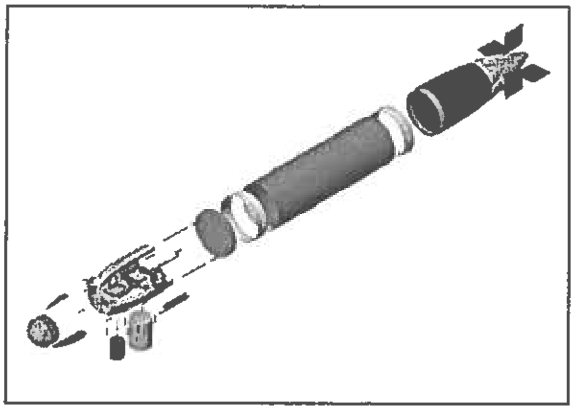

Fig. 2 - New AUV modular design

2.2. ROVs

Remotely Operated Vehicles (ROVs) have been used for a long time in a variety of operation scenarios, ranging from routine underwater visual inspection to intervention in hostile environments. These vehicles are physically connected to the surface by an umbilical cable that provides power and communications.

The LSTS has been developing and operating an electric ROV for the last 3 years. This vehicle is being developed for the project Inspection of Underwater Structures (IES), which concerns the design and implementation of an advanced low cost system for the inspection of underwater structures.

The ROV frame, hull and thrusters are a customized version of the Phantom 500 model from Deep Ocean Engineering (Fig. 3). A new sealed cylinder has been installed to house electronics and sensors and the crash frame has been enlarged to 1.2 meters of length, 60 cm of height and 60 cm of width. Overall, the ROV weights about 100kg in the air.

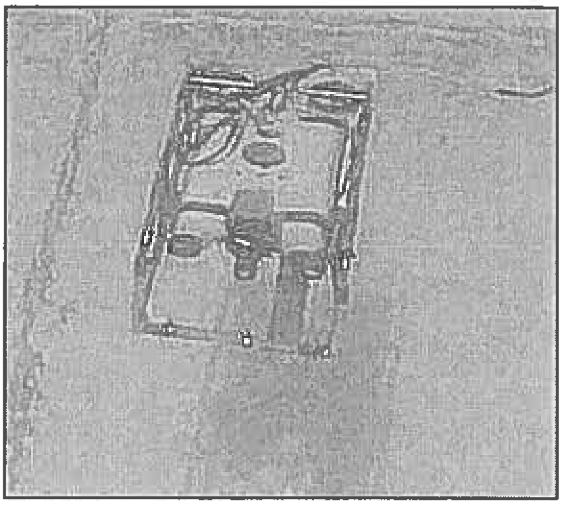

Fig. 3 The IES remotely operated vehicle

Except for the ROV frame, hull and thrusters, all the other components and systems were designed and implemented at LSTS. Currently, the main characteristics are summarized in the following table:

Inspection	Video Camera, *Inspector*, zoom 12:1 (ROS) Pan and Tilt unit (Imenco) 600W of light (DSP&L)
Navigation	Doppler Velocimeter, *Argonaut* (Sontek) Inertial Unit, *HG1700* (Honeywell) Digital Compass, *TCM2* (PNI) Acoustic Beacons, LBL 20-30KHz
Thrusters	4 DC Motors, 120V, 1/8 HP (Bodine)
Umbilical	Customized video, Ethernet and power (Falmat) 300 meters long Neutrally buoyant in fresh water Electrical slipring at the surface
On-board Computer	PC-104 Technology QNX Real Time Operating System CAN Local Bus Ethernet interface with the console

One of the partners of the consortium behind the project is APDL, the port authority in Leixões, Porto, which is the second largest port in Portugal. During the last year, the project has entered its final stage and, naturally, the ROV has been extensively used for several different inspection missions in the harbor. The vehicle has successfully operated in near-zero visibility, taking high quality video footage of several underwater structures. During these demonstration missions, other potential end-users showed interest in the system, so a few other missions have already been planned for 2003, ranging from inspection in harbors and dams to coastal water archaeological missions.

3. SYSTEMS AND TECHNOLOGIES

During the last couple of years the LSTS has been developing a set of subsystems to be integrated in the underwater vehicles and support equipment. Due to the considerable complexity of some of these systems, the adopted approach has consisted on:

- Development of application oriented solutions, taking into account the requirements of the potential end-users;
- Design of modular, reconfigurable, reusable open systems, both in hardware and in software;
- Implementation of PC-based control using COTS technology;
- Development of advanced navigation and control algorithms, squeezing the maximum performance out of the available sensors and actuators.

Following this strategy, the LSTS has gained valuable technological expertise in a wide range of areas, described in the remainder of this section.

3.1. PC104 computational systems

Several computational systems have been assembled in the last few years. Following the strategy described above, the adopted form factor was the PC-104, which is a small size version of the standard ISA/PCI bus. There is a wide choice of boards commercially available from a variety of vendors, with new features being added frequently.

After a market survey, the QNX operating system was chosen to fulfill the requirements of the software architecture (as described below). QNX is a real-time, extensible POSIX-certified OS with a small micro-kernel and a set of optional cooperating processes. This architecture allows us to scale QNX to the particular needs of each vehicle [Silva99]. Although having some deficiencies on thread support, QNX provides most of the required functions for the execution of the onboard software. However, most of the boards commercially available do not have specific drivers for QNX, so they are usually developed at LSTS.

The standard configuration for each vehicle is a main PC-104 stack running the QNX real-time operating system (Fig. 4). The onboard sensors are interfaced through I/O cards on the PC-104 bus: an A/D card and serial port cards. The PC-104 computer system runs the command, control and navigation software, from a hard or flash disk.

A Windows based PC can be connected through an Ethernet cable to the onboard computer. In the case of the ROV, the PC runs the operator console. The PC also runs a Web server providing Web-based access to data from operations, while ROV control is restricted to the operator console. Basically, this computer accepts high-level commands from the console, and informs the console about the state of the system.

In the case of the AUVs, the PC can be connected through an Ethernet cable to an operator console used for mission programming and debugging and for data downloading at the end of a mission.

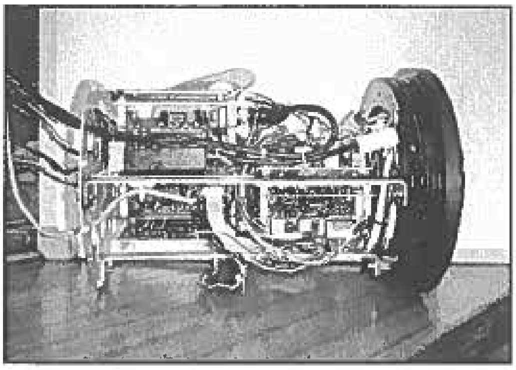

Fig. 4 - ROV PC-104 stack inside a sealed container

3.2. Software architecture

The LSTS has also developed the onboard software of each vehicle. This software is responsible for the control and navigation of the vehicle and also for the command of payload sensors. In the case of the AUVs, the vehicle's behavior is specified by a sequence of basic maneuvers composing the mission, defined before launching. In the case of the ROV, the onboard control system receives motion commands from the console and implements the low level feedback control loops.

The application organization follows a hierarchical layered model, with well defined interfaces and access points. Several agents, running concurrently, are defined at each layer. Each agent will manage a specific subsystem encompassing the relevant information. This approach ensures functional separation, thus increasing code modularity. Each agent is implemented by a different process. In this way, it is quite simple to adapt the software for different vehicles and for different configurations of the same vehicle.

The code was implemented in C++ and, although developed for QNX, its operation is almost system independent. In fact, the only requirement of the operating system is process based multi-tasking. The remaining features of the operating system (process scheduling, priorities, message passing, communications, service identification via names) are encapsulated in classes whose implementation can be adapted to different operating systems without any further change in the code. Libraries of device drivers for sensors and actuators and algorithms for control, guidance and fault management were created for specific vehicle configurations and were designed in such a way that behaviors are a function of the vehicle model parameters, thus permitting code reusability.

3.3. Acoustic navigation

Another major line of work in the LSTS is acoustic navigation, since it is the most popular way of obtaining absolute positioning information underwater. The acoustic navigation system developed at the LSTS is based on a technique usually known as *long baseline* navigation, or LBL. This technique requires the deployment of a set of acoustic beacons, or *transponders*, in the area of operation, and the installation in the vehicle of an omni-directional transducer, capable of transmitting and receiving acoustic signals. During the operation, the vehicle interrogates each beacon, with a given frequency and each transponder replies with another frequency. The computational system of the vehicle measures the turn around time and computes the distance to that transponder. Using a triangulation algorithm and knowing the locations of the beacons the position of the vehicle is then determined.

The exchange of underwater acoustic signals requires an arrangement of elemental building blocks, namely an acoustic transmitter, an acoustic detector and an interface board. All these blocks have been developed at LSTS and, currently, different configurations are being used on the AUV, the ROV and on various navigation beacons (Fig. 5).

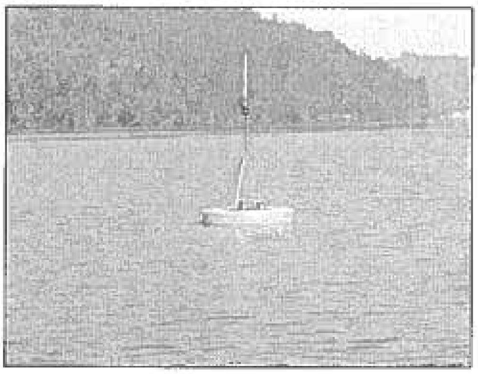

Fig. 5 - Surface buoy with underwater acoustic beacon

3.4. Algorithms for navigation

The main function of a navigation system is to determine the vehicle's own position in the horizontal plane, as the vertical coordinate is given directly from the pressure cell. A navigation system is composed by a set of sensors providing data related to the vehicle motion and an algorithm that receives data from the sensors and outputs an estimate of the vehicle position.

The suite of navigation sensors of each one of the LSTS vehicles includes both on-board sensors and also an external acoustic navigation network (see [Cruz01, Matos99]). The minimal onboard set of sensors is formed by a magnetic compass, a set of tilt sensors and a pressure sensor. Optionally, an inertial navigation unit and an acoustic Doppler velocimeter can be used.

Since the vehicle can be far away from each transponder, there might be a few seconds between position estimates. In the meantime, the navigation system uses dead reckoning information, i.e., velocity and acceleration data, to update the position estimate.

In the case of the ISURUS AUV, the instantaneous velocity is obtained by measuring the propeller rotation speed and the vehicle heading, pitch and roll. Velocity measurements are fused together with range measurements by a Kalman filter based algorithm, taking advantage of the characteristics of each type of data. On the one hand, the vehicle velocity is available at a high rate, but its integration leads to a drift in the estimated position. On the other hand, range measurements, available at a lower rate, can be noisy but do not drift over time. The algorithm updates the estimate of the vehicle position at the same rate the velocity is measured, and corrects it whenever a new range measurement is available, giving the best estimated position in real-time [Matos99]. Besides the estimation of the vehicle position, the algorithm also produces a coarse estimate of the water current (in the horizontal plane).

In the case of the ROV, besides the pressure sensor and the magnetic compass, an inertial navigation unit (HG1700 from Honeywell) and an acoustic Doppler velocimeter (DVL Argonaut from Sontek) are also used. The angular velocities given by the inertial unit are directly used by the heading feedback control loop. The Doppler system gives the velocity relative to the bottom. This information as well as the information obtained form the inertial unit (linear accelerations and angular velocities) are then fused with the data from the pressure cell and the ranges to the transponders to provide as estimate of the vehicle position and attitude in real time. The data fusion algorithm is based on a Kalman filter.

3.5. Control architecture

We organize the operations of our vehicles as a sequence of maneuvers. First we define a basic set of "atomic maneuvers", from which all the maneuvers can be derived. Once we have found a minimal set of atomic maneuvers, we can verify their design for safety. We then compose complex maneuvers, using the elemental maneuvers as building blocks. This enables us to always design correct maneuvers – maneuvers that meet the given specifications – even in the presence of disturbances. From the operator's perspective, this means having at his disposal a set of commands with which a complex mission can be planned and executed. The set of commands is designed to comply with the operational requirements while ensuring proper termination, or adequate fault handling. In our setting, maneuvers can be designed to accommodate interactions with an operator if that is feasible. For example, tele-operation for the ROV is defined as an elemental maneuver.

One of the aspects of maneuver design concerns trajectory generation and tracking. Underwater vehicles are designed to perform missions that are composed of several tasks. These tasks may involve the inspection of underwater structures, data collection, map building, etc. The problem of designing trajectories for each mission requires the intervention of a mission expert, to capture the domain knowledge, and the consideration of the dynamic models of each vehicle. The quality of the models is strongly related to the performance of the trajectory, and hence task performance. Traditionally, the mission expert is not an expert on modeling and control systems. Hence, trajectory generation does not take into account the dynamical models of each vehicle and it is up to the control system to handle this additional "disturbance". This obviously results in poor performance and, even worse, on undesirable behavior when it comes to mission execution, i.e., incorrect trajectory specification.

3.6. Advanced control systems

The design of control systems for underwater vehicles is a complex and challenging task. The preparation and execution of missions for parameter identification is very resource consuming, so the existing models are usually inaccurate, particularly in the cases where the physical configuration of the vehicles change frequently. Furthermore, motion is usually allowed in several degrees of freedom (particularly for ROVs), which are controlled independently although having nonlinear coupling.

Even for reasonable models, there is often some difficulty with the definition of the performance index. Among other things, this index has to reflect the tradeoff between trajectory smoothness and tracking accuracy.

Our approach organizes the design of the control system in three main modules: user interface, trajectory generation and feedback control. Only the user interface model differs from the AUV to the ROV system, as the interaction between the AUV and the user only occurs offline. The approach for trajectory generation is based on techniques that take advantage from differential flatness property. For feedback control design, we have been using standard non-linear control techniques, since linear decoupled controllers typically result in low bandwidth feedback loops.

4. CURRENT DEVELOPMENTS

4.1. PISCIS Project

The **PISCIS** project concerns the design and implementation of a modular, advanced and low cost system for oceanographic data gathering that includes two autonomous underwater vehicles, an acoustic positioning system, a docking station and modular sensing packages. The PISCIS system is configurable for applications in real time oceanography, bathymetry, underwater archaeology, and effluents monitoring. The project started in December 2002, has a total duration of 3 years, and is funded by PROGRAMA POCTI Medida 2.3.

The main innovations of the PISCIS system are:

- Coordinated operation. Vehicles exchange limited amounts of data and commands to coordinate their operation.
- Advanced control systems. The PISCIS control system includes automated operation modes that can be configured according to each specific operational scenario.
- Sensor based missions. The trajectories of the AUVs are specified in real time according to the data being gathered throughout the mission.

The problem of specification and design of coordinated control for new concepts for the operation of networked vehicle and sensor systems poses new challenges to control engineering [Sousa01, Sousa02]. These challenges entail a shift in the focus of control theory - from prescribing and commanding the behavior of isolated systems to prescribing and commanding the behavior of distributed interacting systems - and requires a convergence of methods and techniques from control engineering, networking and computer science [Simsek01]. The coordinated motion of the vehicles supported by the docking station allows for rapid ocean sampling, an essential requirement for the synoptic observation of oceanographic phenomena. Furthermore, vehicle coordination is restricted to the exchange of data and commands at pre-determined waypoints due to the vehicles limited communication capabilities.

A framework for the representation, formal specification, and control synthesis for networked vehicle systems will be developed. The framework relies on techniques from set theory and dynamic optimization. First, we represent all entities, their dynamic behavior, and the relations among themselves. We use reachable sets to describe the evolution of a dynamic system, invariant sets to describe the locations where an entity is ensured to remain, and solvable sets to describe the locations from which a system can evolve to reach a given set. Second, we specify operations on these entities, and express the specification in a formal language. Third, we write partial plan specifications. Fourth, we define a planning procedure that results in a data structure defining all controller specifications preceding the controller design for which the logical relations are already satisfied. Fifth, we use techniques from dynamic optimization to synthesize controllers that either implement the plan, or prove that the plan is not feasible.

Another thrust for this project is the problem of adaptive sampling of oceanographic phenomena with heterogeneous AUVs with limited capabilities. The fundamental idea underlying adaptive sampling is to increase the survey efficiency by concentrating measurements in regions of interest. Thus, to map an oceanfront, for example, one might first run a very coarse survey to localize the front, and then concentrate operations in the front vicinity.

4.2. KOS Project

The **KOS** project is a follow-up of IES, enhancing the inspection capabilities and allowing the ROV to perform simple intervention tasks. This project is funded by PROGRAMA POCTI Medida 2.3 and is scheduled to begin in the summer of 2003.

In the IES project, the inspection task relies solely on the video images, with no information regarding the scale or the size of the features being inspected. For the KOS project, there will be a laser scale projected onto the scene to allow for size measurement, a line scanning sonar yielding acoustic ranges to the target and a digital still camera providing high-resolution pictures. As far as intervention is concerned, a 2 DOF electric manipulator will be attached to the frame.

The KOS project also aims at improving the performance of the ROV system, by regarding the control of the robotic arm, the pan & tilt unit and ROV as an integrated problem. An illustrative example is the coordinated control of the orientation of the pan & tilt unit and the attitude of the ROV, to maintain an inspection target in the camera field of view.

The control problems to be solved were identified during mission held in several operational scenarios under the IES project [Fraga01] and require the use of advanced control algorithms. The major difficulties envisaged are

- wave induced disturbances close to the surface or submerged structures,
- disturbances induced by the interaction between the thruster and walls,
- currents produced by tidal variation, and
- motion induced by the support vessel in sea operations.

5. CONCLUSIONS

In this paper, the AUV and ROV development programmes at the LSTS were reviewed in the context of the recent and exciting possibilities offered by the operation of networked vehicles and distributed sensor systems for oceanographic field studies. This review was organized in terms of the projects executed and of the technologies developed at the laboratory.

The LSTS has accumulated valuable expertise in several areas related to underwater systems and is currently applying it to new projects with demanding requirements.

The major technical developments have been driven by the requirements identified in real applications and most of the solutions obtained have actually been validated in successful operational missions. The same approach is intended for the new advances in underwater robotic systems and related technology.

ACKNOWLEDGEMENTS

This material is based upon work supported by Fundação da Ciência e Tecnologia under project CorDyAL and by Agência da Inovação under projects PISCIS and KOS - PROGRAMA POCTI.

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